

TRANSVERSE TO LONGITUDINAL EMITTANCE EXCHANGE BEAMLINE AT THE A0 PHOTOINJECTOR*

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Abstract

The FNAL A0 Photoinjector is being reconfigured to test the principle of transverse to longitudinal emittance exchange as proposed by Cornacchia and Emma, Kim and Sessler, and others. The ability to perform such an exchange could have major advantages to FELs by reducing the transverse emittance. Several schemes to carry out the exchange are possible and will be reported separately. At the Fermilab A0 Photoinjector we are constructing a beamline to demonstrate this transverse to longitudinal emittance exchange. This beamline will consist of a dogleg, a TM₁₁₀ 5 cell copper cavity, and another dogleg. The beamline is designed to reuse the bunch compressor dipoles of the photoinjector, along with some existing diagnostics. Beamline layout and simulations are presented. Emittance dilution effects are also discussed.

INTRODUCTION

In 2002 Cornacchia and Emma introduced a scheme to exchange a beam's longitudinal emittance with a transverse emittance using a TM₁₁₀ mode cavity in the dispersive section of a magnetic chicane.[1] Such a beam would have a smaller transverse emittance than can be produced with a laser driven RF gun and would be suitable to drive an FEL.

K.J. Kim proposed a different scheme to place a TM₁₁₀ mode cavity between two doglegs to effect the same exchange.[2] This scheme has an advantage over the original scheme in the limit of a thin cavity because the emittances are uncoupled after the exchange. An experiment using unequal transverse emittances is being planned at the Argonne Wakefield Accelerator [3].

We plan to do a proof of principle emittance exchange experiment at the FNAL A0 Photoinjector using the scheme proposed by K.J. Kim. We discuss the beamline design and simulations. Effects that can potentially dilute the exchange are also discussed.

EMITTANCE EXCHANGE OPTICS

The optics of the emittance exchange have been discussed at length in References 1 and 2. The goal is to design a beamline such that the 4x4 transport matrix is of the form

$$M = \begin{pmatrix} 0 & B \\ C & 0 \end{pmatrix} \quad (1)$$

where the phase space coordinates are $x, x', z, \Delta p/p$. Each element is a 2x2 block.

To accomplish this goal, one can use a cavity operating in the TM₁₁₀ mode. Such a mode has a longitudinal electric field proportional to x that passes through a null on axis and a uniform deflecting magnetic field 90° later. It is because of the magnetic field that this mode is often called the deflecting mode. The emittance exchange takes advantage of the longitudinal electric field to change a dispersion induced correlated momentum $\Delta p/p$ vs. x of the beam, while at the same time providing a transverse kick as a function of arrival time. The transport matrix of a single pillbox cavity for this mode is

$$M^{cav} = \begin{pmatrix} 1 & L & kL/2 & 0 \\ 0 & 1 & k & 0 \\ 0 & 0 & 1 & 0 \\ k & kL/2 & k^2L/4 & 1 \end{pmatrix} \approx \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & k & 0 \\ 0 & 0 & 1 & 0 \\ k & 0 & 0 & 1 \end{pmatrix} \quad (2)$$

where L is cavity length and the cavity strength

$$k = \frac{eV_l}{aE}.$$

E is the beam energy (16MeV), V_l is the integrated voltage at distance a transverse to the axis.[4] The cavity will be a 5 cell copper cavity and is discussed in these proceedings.[5]

One can segment the beamline into three sections, the before cavity section, the cavity itself, and the after cavity section. In this case the matrix for the beamline takes the form

$$M = M^{ac} M^{cav} M^{bc}. \quad (3)$$

We assume that the beamline contains only magnetic elements except for the deflecting mode cavity. If the before cavity section generates some dispersion η and slope η' , one can show that the cavity strength is given by

$$k = -\frac{1}{\eta}. \quad (4)$$

It is interesting to note that this result is independent of the thin lens approximation.

In order for the transport matrix to give the block form of Equation 1, the transport matrix for the after cavity section must satisfy

$$\begin{aligned} M_{16}^{ac} &= M_{11}^{ac} \eta + M_{12}^{ac} \eta' \\ M_{26}^{ac} &= M_{21}^{ac} \eta + M_{22}^{ac} \eta' \end{aligned} \quad (5)$$

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where the thin cavity approximation has been used.[6] In the case that the thin cavity approximation cannot be used, there is no solution that will give a completely uncoupled emittance exchange. We note that Equations 5 are only dependent on the dispersion function and its slope prior to the cavity, the other elements of M^{bc} do not affect the solution. A consequence of Equations 5 is that any solution that removes the dispersion in the absence of the cavity, such as the chicane proposed in Reference 1, cannot produce an uncoupled emittance exchange, as a minus sign is needed on the right hand side.

One type of solution was proposed by H. Edwards.[7] This design can use a bend followed by a quad or a dogleg to generate dispersion at the deflecting mode cavity. The beamline after the cavity consists of a quadrupole magnet followed by a dipole. In thin lens approximation, this will produce an uncoupled emittance exchange if the dipole bend angle and quadrupole focal length after the cavity satisfy

$$\theta = -\frac{\eta + d_1\eta'}{d_2 + \frac{1}{2}}$$

$$f = \frac{-\theta(d_2 + \frac{1}{2})^2}{\eta + \eta'(d_1 + d_2 + \frac{1}{2})} \quad (6)$$

where l are the dipole bend length, d_1 is the drift from the cavity to the quadrupole and d_2 is the drift between the quadrupole and dipole. We have chosen not to use this solution because of space constraints in the A0 cave.

BEAMLINE LAYOUT

Figure 1 shows the beamline layout that is being installed at A0. After the RF gun and booster cavity, not shown, there is a diagnostics channel.[8] Dipole one starts the emittance exchange line. After the second dogleg there is a short diagnostics channel to measure the transverse emittance and bunch length. A vertical bending spectrometer will be used to measure the momentum spread of the beam after the exchange. The first dipole of the exchange line (D1) can be turned off to allow for operation of other experiments.

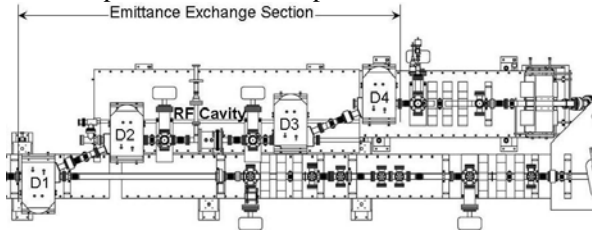


Figure 1: Top view of the A0 Photoinjector emittance exchange line. The upper beamline is for emittance exchange. The lower line is for other experiments. Beam direction is to the right.

The transverse emittance before and after the exchange will be measured using the multislit method.[8] The bunch length and momentum spread prior to the exchange can be measured in the straight ahead line. We plan to use a streak camera to measure the bunch length prior to the exchange and a Martin-Puplett interferometer to

measure after the exchange. The energy spread will be measured after a spectrometer magnet using an optical transition radiation screen to image the beam size. Ports are available on Dipole 3 and the spectrometer to view synchrotron radiation.

SIMULATIONS

Figure 2 shows the β and dispersion function through the emittance exchange beamline with an unpowered cavity. A quadrupole doublet upstream of the first dipole is adjusted to provide focusing at the cavity. Edge angles on the dipoles provide the remaining focusing.

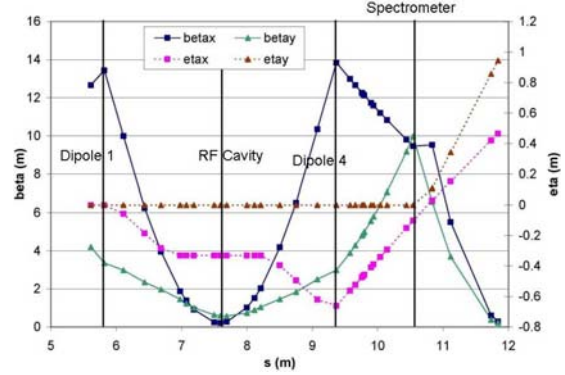


Figure 2: Envelope and dispersion functions through emittance exchange line with no cavity. Distance is from the cathode.

The first dogleg is designed to produce a dispersion of 33cm at the entrance to the 5 cell cavity. The second dogleg increases the dispersion of 66 cm with no RF in the cavity. The spectrometer bends the beam 45 degrees into the floor.

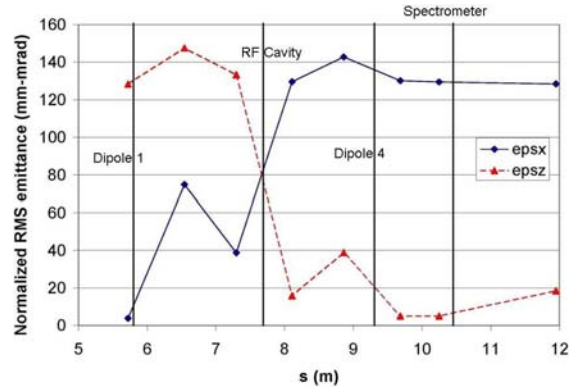


Figure 3: Evolution of the exchanged emittances along the emittance exchange beamline.

ELEGANT was used to simulate the emittance exchange using a bi-gaussian distribution in each phase space.[9] The cavity is simulated as a single cell by using the thick cavity matrix of Equation 2. Figure 3 shows the evolution of the emittance exchange from the start of the first dipole through the beam dump. The initial transverse normalized emittances are 4 mm-mrad, matched to the above ellipse parameters. The longitudinal normalized emittance is 130 mm-mrad. The initial bunch length is 1.5mm, and the momentum spread is 0.5%. The

longitudinal ellipse is chirped to compress the bunch to 1.0 mm in the center of the cavity.

Figure 4 shows the projected emittance evolution with no RF cavity. The transverse emittance increase is due to the dispersion generated in the beamline.

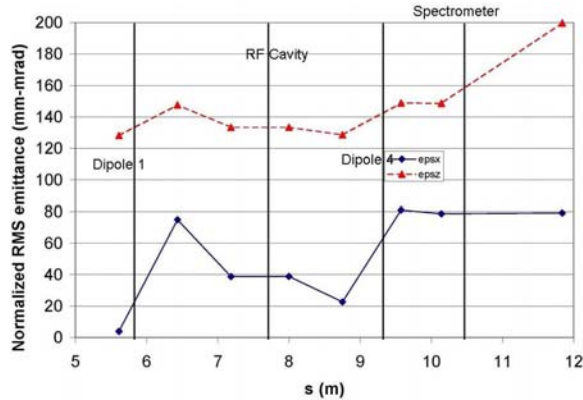


Figure 4: Evolution of the exchanged emittances along the emittance exchange beamline without the cavity.

More detailed simulations are planned. These will include self field effects, such as space charge and coherent synchrotron radiation, 3D field maps of the deflecting mode cavity. Ultimately start to end simulations will be developed.

EMITTANCE DILUTION

As mentioned above, a perfect emittance exchange occurs only if the transport matrix is identically zero on the block diagonals. Any non-zero element will couple the two emittances and yield larger final emittances.

The finite length of the cavity will introduce nonzero elements on the diagonal blocks. These matrix elements will lead to an increase in the emittance according to Equation 19 of Reference 1. This corresponds to 0.1% increase for the larger emittance, and a doubling of the smaller emittance. The above simulations show a 1% increase in the large emittance and a 30% increase in the smaller emittance. A simpler simulation gave an estimate of 10%. [7]

Self field effects can also have an effect on the emittance exchange. We know that space charge effects lead to emittance growth at A0 even with charge on the order of 1nC.[8] Another effect that may be an issue is Coherent Synchrotron Radiation (CSR). This can lead to emittance blowup in the exchanged planes.

Most analytical approaches to CSR assume a one dimensional model of the electron bunch where the transverse dimensions of the beam are ignored. The validity of this model is quantified by the Derbenev criterion

$$\frac{\sigma_x}{\sigma_z} 2^{1/3} \left[3 \frac{\rho^2}{\sigma_z^2} \right]^{1/9} \ll 1$$

where σ_x and σ_z are the transverse and longitudinal bunch sizes, and $\rho = 0.743\text{m}$ is the bending radius of the dipole.[10] The Derbenev criterion is on the order of 0.5

in the first dogleg, and of order 1 in the second dogleg. If the bunch is compressed further then the Derbenev criterion can approach 8 in the third dipole of the exchange beamline. This means that the 1D approximations are not generally valid and simulations are needed to estimate the effect.

The bunch length is 250 μm after the exchange so CSR may also be an issue for the energy spread measurement. The CSR in the spectrometer would lead to increased energy spread not due to the exchange, and giving a larger apparent longitudinal emittance. For our spectrometer the Derbenev Criterion is 15. Simulations certainly need to be done for this case.

The coherent power radiated scales as the square of the bunch charge. CSR may be mitigated by using reduced bunch charge. We plan to explore bunch charges in the range of 100pC to 1 nC for this experiment and it will be interesting to see if we can observe and characterize CSR effects after verification of single particle dynamics at low charge.

CONCLUSION

A transverse to longitudinal emittance exchange beamline is being constructed at the FNAL A0 Photoinjector. We have presented the beamline design and initial simulations of the exchange. Investigation has begun into effects that will dilute the exchange, and start to end simulations are under development.

Necessary modifications to the A0 Photoinjector have already occurred to accommodate the new beamline. The exchange experiment will be installed this summer and data taking will start shortly thereafter.

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